National Institute of Standards and Technology
U.S. Department of Commerce

MEASUREMENT SCIENCE FOR

Disaster-Resilient Structures and Communities

What is the problem?

Natural and technological disasters cause an estimated $55 billion in average annual costs (and growing), with single catastrophes like Hurricane Katrina and future "Kobe" earthquakes causing mega-losses exceeding $100 billion. Existing extreme load-related prescriptive requirements of building codes, standards, and practices stifle design and construction innovation and increase construction costs. The risk in large disaster-prone regions of the nation is substantially greater now than ever before due to the combined effects of development and population growth. As noted by the National Science and Technology Council, "...a primary focus on response and recovery is an impractical and inefficient strategy for dealing with [natural disasters]. Instead, communities must break the cycle of destruction and recovery by enhancing disaster resilience." [1]

The link between basic research and building codes, standards, and practices is weak. Further, the measurement science is lacking to: 1) predict structural performance to failure under extreme loading conditions: 2) predict disaster resilience at the community scale; 3) assess and evaluate the ability of existing structures to withstand extreme loads; 4) design new buildings and retrofit existing buildings using cost-effective, performance-based methods; and 5) derive lessons learned from disasters and failures involving structures.

Why is it hard to solve?

The natural processes that produce risks in the built environment and the information relative to those risks for use by design professionals, standards developers, and emergency planners are not well understood. Cost-effective mitigation strategies that improve the performance of structural systems are complex, often lying outside the breadth of the prescriptive procedures that dominate building codes, standards, and practices. Methods for transferring basic research results into practice are limited. The engineering community lacks standard methods of predicting, evaluating, and assessing the disaster resilience of structures as they respond to extreme loads. Communities lack standard methods of assessing disaster resilience at the community scale for use in making disaster preparedness and mitigation decisions.

The disaster resilience of structures and communities is determined by building codes, standards, and practices used when structures were built—most older structures have only minimal resilience. Most codes, standards, and practices are highly prescriptive, simplified, and inconsistent

[1] National Science and Technology Council, Grand Challenges for Disaster Reduction—A Report of the Subcommittee on Disaster Reduction, June 2005.

with respect to risk—stifling innovation and increasing cost. There is a lack of validated tools and metrics to evaluate structural and community performance, as well as the risks to which they are exposed—the lack of accurate models increases conservatism and decreases cost-effectiveness. Codes and standards are developed by private sector organizations that often lack the resources needed to develop the technical bases to improve them in a timely manner. Practices, codes, and standards used in design, construction, and retrofit are based largely on research performed or supported by the government.

Why BFRL?

Measurement Science for Disaster-Resilient Structures and Communities supports the Building and Fire Research Laboratory (BFRL) mission of promoting U.S. innovation and competitiveness by anticipating and meeting the measurement science, standards, and technology needs of the U.S. building and fire safety industries in ways that enhance economic security and improve the quality of life. This program fulfills a national knowledge transfer role that is not well-supported by a fragmented U.S. construction industry. The program supports the BFRL core competency in performance, reliability, and resilience of structures and communities under extreme loads. Finally, NIST has statutory responsibilities including: the Fire Prevention and Control Act (1974); the National Earthquake Hazards Reduction Program Reauthorization Act (1977, amended 2004); the National Windstorm Impact Reduction Act (2004); and the National Construction Safety Team Act (2002).

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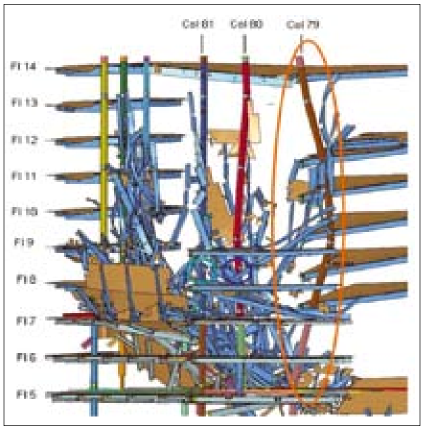
Investigation of the World Trade Center Disaster

On August 21, 2002, NIST announced its building and fire safety investigation of the World Trade Center (WTC) disaster. The WTC Investigation was conducted under the authority of the National Construction Safety Team (NCST) Act, which was signed into law on October 1, 2002.

The specific objectives of the investigation were to: 1) determine why and how the towers, WTC 1 and WTC 2, collapsed following the initial impacts of the aircraft and why and how the WTC 7 building collapsed; 2) determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response; 3) determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and 4) identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.



Graphic showing the buckling of WTC 7 Column 79 (circled area), the local failure identified as the initiating event in the building's progressive collapse.

NIST completed the study of the World Trade Center towers and released the final report in October 2005. The final report entitled, "Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers" (NCSTAR 1) and the 42 companion reports are available on the NIST WTC web site: *http://wtc.nist.gov/reports_october05.htm*.

The results of this extensive research led to the conclusion that the tragic consequences of the September 11, 2001, attacks were directly attributable to the combination of initial structural damage and the resulting multi-floor fires resulting from the impact of large, jet-fuel laden commercial airliners into the WTC towers. Buildings for use by the general population are not designed to withstand attacks of such severity; building regulations do not require building designs to consider aircraft impact. In U.S. cities, there has been no other experience with a disaster of such magnitude, nor has there been any in which the total collapse of a high-rise building occurred so rapidly and with little warning.

NIST also completed the investigation of WTC 7, the third building that collapsed on September 11, 2001. The study found that the fires in WTC 7, which were uncontrolled but otherwise similar to fires experienced in other tall buildings, caused an extraordinary event. Heating of floor beams and girders caused a critical support column to fail, initiating a fire-induced progressive collapse that brought the building down. A key factor leading to the eventual collapse of WTC 7 was thermal expansion of long-span floor systems at temperatures hundreds of degrees below those typically considered in current practice for fire resistance ratings. WTC 7 used a structural system design in widespread use.

As a result of its investigation of the WTC towers, NIST compiled a list of 30 recommendations to improve the safety of tall buildings, occupants, and emergency responders based on its investigation of the procedures and practices that were used for the WTC towers. The recommendations call for action by specific entities regarding standards, codes and regulations, their adoption and enforcement, professional practices, education, and training; and research and development. Additionally, as a result of the investigation of WTC 7, NIST has issued one additional recommendation and reiterated 12 of the recommendations from the WTC towers investigation.

Responding to the recommendations, the International Code Council (ICC) has adopted 23 code changes that were incorporated in the 2009 edition of the International Building Code and the International Fire Code. In addition, the National Fire Protection Association (NFPA) approved fifteen changes that were incorporated into the 2009 editions of the NFPA 5000 Building Code, the NFPA 1 Fire Code, and the NFPA 101 Life Safety Code. These far-reaching building and fire code changes will lead to future buildings—especially tall structures—that are increasingly resistant to fire, more easily evacuated in emergencies, and safer overall for occupants and emergency responders. NIST is continuing to work with the codes and standards bodies and the technical community toward implementing additional changes to codes and standards based on the recommendations of the WTC investigation.

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Structural Performance Under Multi-Hazards

The fundamental new idea guiding this program is that disaster resilience can be enhanced significantly by developing a robust capability to predict the effects of hazards on the performance of complex structural systems and on community-wide response.

The scope of the BFRL's measurement science research includes extreme wind engineering and structural fire resistance with progressive collapse and multi-hazard failure analysis being cross-cutting research topics. Development of cost-effectiveness tools for evaluating multi-hazard risks at the community scale is a significant part of the research plan.

The program consists of five research thrusts: 1) develop validated tools that

The US-90 Biloxi-Ocean Springs bridge (looking west toward Biloxi from the east shore). Simply supported superstructure spans were displaced and dropped north off their piers due to storm surge and wave actions during Hurricane Katrina in 2005.

predict structural performance to failure under extreme loading conditions; 2) develop community-scale loss estimation tools to predict consequences of disasters, leading in turn to increased resilience; 3) develop validated tools to assess and evaluate the capabilities of existing structures to withstand extreme loads; 4) develop performance-based guidelines for cost-effective design of new buildings and, where warranted, rehabilitation of existing buildings; and 5) derive lessons learned from disasters and failures involving structures.

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Photo Credit: Earthquake Engineering Research Institute (EERI), James L. Stratta

Earthquake damage to the Olive View Hospital in San Fernando, CA, from the 1971 earthquake.

National Earthquake Hazards Reduction Program (NEHRP)

Although damaging earthquakes occur infrequently in the U.S., they strike with little or no warning, with potentially catastrophic consequences. A 2003 report by the Earthquake Engineering Research Institute (EERI)[1] states that a single large earthquake in an urban area could easily result in direct and indirect economic losses between $100 billion and $200 billion. While seismic provisions for new buildings in U.S. model building codes have gradually been improved, their focus on life safety for their occupants has led to costly prescriptive design procedures. The existing building stock is much more vulnerable to earthquake damage than newly designed buildings and is likely to be in use for many decades. Cost-effective seismic evaluation and rehabilitation methodologies are not widely available or applied.

Four Federal agencies—FEMA, NIST, NSF, and the US Geological Survey (USGS)—comprise the NEHRP partnership and perform research and implementation activities related to earthquake hazard mitigation in the U.S. under directions provided by NEHRP authorization legislation. The most recent NEHRP reauthorization occurred in 2004. That reauthorization directed that NIST be established as the NEHRP lead agency, with responsibility for program coordination and planning for the four NEHRP partner agencies. The same authorizing legislation makes NIST responsible for performing applied earthquake engineering research under the auspices of NEHRP.

BFRL is targeting six general areas of measurement science research to support near- and long-term improvements to building and community disaster resilience with respect to the earthquake threat:

- technical support for building code development;
- performance-based seismic engineering;
- national design guidelines;
- evaluated technology dissemination;
- enhanced design productivity and interoperability; and,
- improved evaluation and strengthening for existing buildings.

NEHRP research and implementation efforts will result in reduced societal risk, cost, and operational impacts from earthquakes on individuals, businesses, and government. The program will also foster a transformation from prescriptive to performance-based design codes and standards, enabling innovation in materials, technologies, and system designs and fostering cost-effectiveness.

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[1] Earthquake Engineering Research Institute, Securing Society Against Catastrophic Earthquake Losses: A Research and Outreach Plan in Earthquake Engineering, June 2003.